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Magnetomechanical effects in textured polycrystalline $Tb_{76}Dy_{24}$

J. Graetz,[a] N. Good, and B. Fultz
Division of Engineering and Applied Science, California Institute of Technology, Pasadena, California 91125

J. Dooley and R. Chave
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109

Uniaxial stress-strain measurements were performed on polycrystalline $Tb_{76}Dy_{24}$ alloys which exhibit ''giant magnetostriction'' at cryogenic temperatures. The Young's moduli were reduced by up to a factor of five at 77 K, in comparison to their values at 300 K. We attribute this reduction to a mechanical compliance from domain rotation. Large mechanical hysteresis is also found in nominally elastic stress-strain curves measured below the Curie temperature. Hysteretic curves from 0 to 25 MPa demonstrate up to 19% dissipation of the applied mechanical energy. The anisotropy of thermal expansion was also measured and used as a parameter for the degree of crystallographic texture. This anisotropy was correlated to bulk magnetostriction and to mechanical hysteresis.
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INTRODUCTION

Alloys of Tb–Dy exhibit ''giant magnetostriction'' at cryogenic temperatures, undergoing strains of nearly 1% in single crystals. Polycrystalline materials with controlled crystallographic texture have achieved magnetostrictive strains of half that of single crystal samples.[1–3] The strong magnetoelastic coupling responsible for magnetostriction also permits stress to induce domain wall motion, which can result in significant energy dissipation. A previous study on magnetomechanical damping interpreted the hysteretic loss with a model involving magnetization jumps within individual domains.[4] Measurements on Terfenol-D show on the order of 10% fractional energy dissipation at room temperature.[5]

There is currently a large demand for low temperature energy absorbing materials for damping vibrations in space structures such as telescopes and large antennas. Conventional viscoelastic damping relies on movements of atoms, which become negligible at cryogenic temperatures. In magnetostrictive materials, the damping of vibrational energy occurs by the movement of magnetic domains. We show a 19% dissipation of the mechanical energy of polycrystalline Tb–Dy at 77 K.

MATERIALS PREPARATION

Commercial grade (total purity 99.7%) and high purity (99.94%) alloys of polycrystalline Tb–Dy were received as-cast from the Ames Laboratory Materials Preparation Center. A sample composition of $Tb_{76}Dy_{24}$ was chosen to minimize the magnetic anisotropy at 4 K.[6] The magnetization rotates easily in the basal plane of the hcp structure. The desired crystallographic texture would provide good alignments of the basal planes of the different grains. The as-cast ingots exhibit a significant undesirable radial crystallographic texture. Samples were initially cold rolled by 35% and recrystallized in an inert atmosphere at 900 °C. This was performed with the intent of reducing the crystallographic texture and achieving a more equiaxed grain size. Samples were subsequently cold rolled by 55%. The process of plastic deformation induces slip across the hexagonal basal planes. Significant slip in this plane causes the *c* axis to align parallel to the direction of the applied stress σ. Finally, the samples were annealed at 350 °C to relieve internal stresses.

EXPERIMENTAL PROCEDURE

Strain gages were affixed to the cuboidal samples to measure strains in the *x* and *y* directions (see Fig. 1). This configuration allowed for measurements of both the *x*-axis compression and *y*-axis expansion at room and liquid nitrogen temperatures. The samples were placed in a dewar filled with liquid nitrogen and affixed to a rigid base plate. The surface temperature of the sample was measured using a silicon diode thermometer. The specimen was then subjected to compressive stress in the *x* direction from a computer-controlled Instron load frame. Stresses varied from 0 to 25–40 MPa. The crossbeam motion was 0.5 mm/min, resulting in roughly 0.02–0.08 Hz frequency for cyclic testing. Measurements were repeated on the same sample at 300 K.

Measurements of the anisotropy in thermal expansion were used to obtain a parameterization of the crystallographic texture of the sample. Measurements were performed on three orthogonal directions of each sample from 30–

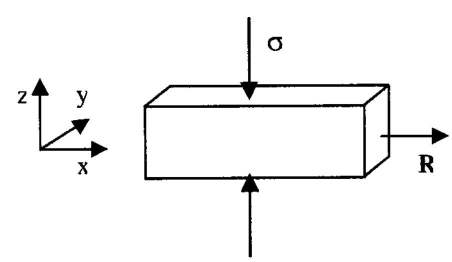

FIG. 1. Geometry of plane rolled sample where *R* and σ denote the direction of rolling and applied stress, respectively.

[a]Electronic mail: graetz@hyperfine.caltech.equ

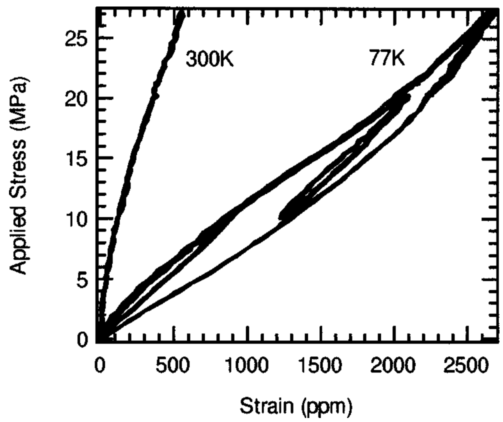

FIG. 2. Stress-strain curves for the commercial grade (99.7%) $Tb_{76}Dy_{24}$ sample, showing major and minor loops. A room temperature stress-strain curve without hysteresis is also shown.

300 °C under an inert atmosphere using a Perkin–Elmer TMA-7 thermomechanical analyzer. Thermal expansion is expected to become more anisotropic for increased crystallographic texture, with the ratios of measured coefficients of thermal expansion in the *c* axis to those in the basal plane ranging from 1.0 for an isotropic material to 4.5 for a single crystal.

RESULTS

Cyclic stress-strain curves measured on a sample of $Tb_{76}Dy_{24}$ of commercial purity are shown in Fig. 2. The Young's modulus at 300 K is 49.6 GPa for the stress range of 0–27 MPa. At liquid nitrogen temperature the Young's modulus is 10.0 GPa. There is also a pronounced hysteresis in the stress-strain curve below the Curie temperature. Similar measurements performed on a high purity sample of $Tb_{76}Dy_{24}$ are shown in Fig. 3. In the high purity sample, Young's modulus at 300 K is 57.2 GPa, similar to the commercial grade specimen. At liquid nitrogen temperature the Young's modulus is 17.2 GPa for the stress range of 0–37 MPa. The integral over the hysteresis loop measured in the high purity sample is approximately half of that observed in the commercial grade material. Intermediate cyclic stress-strain curves were also measured 77 K, providing the minor loops shown in Figs. 2 and 3. The widths of the hysteresis loops in the stress-strain curves are reduced at higher applied stresses for both samples.

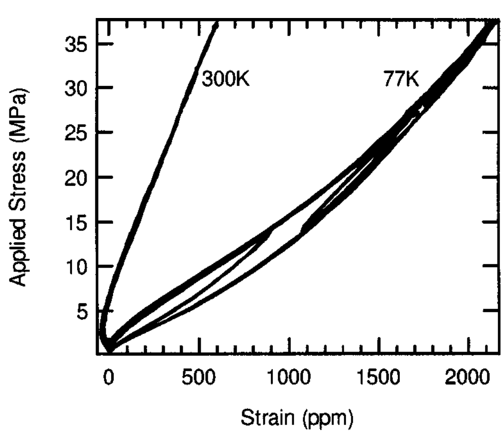

FIG. 3. Stress-strain curves for the high purity (99.94%) $Tb_{76}Dy_{24}$ sample, showing major and minor loops. A room temperature stress-strain curve without hysteresis is also shown.

TABLE I. Total energy dissipation of polycrystalline Tb–Dy over one cycle from 0 to 27 MPa. Fractional dissipation is defined as the area of the hysteresis loop to the mean area under loading and unloading curves.

	Fractional dissipation (%)	Energy ($0<\epsilon<2700$ ppm) (J/mol)
Commercial purity	19.2	0.297
High purity	14.1	0.235

DISCUSSION

At 300 K, Figs. 2 and 3 show the Young's moduli to be 49.6 and 57.2 GPa for the commercial purity and high purity samples, respectively. These data are in reasonable agreement with the values of 59.1 GPa reported for $Tb_{76}Dy_{24}$.[7] A much more interesting feature of Figs. 2 and 3, however, are the approximately fivefold and threefold reductions in Young's moduli at 77 K for the commercial purity and high purity samples, respectively. The Curie temperature of $Tb_{76}Dy_{24}$, is approximately 180 K, so the material is ferromagnetic at 77 K and paramagnetic at 300 K. We attribute the large reduction in Young's modulus to the presence of magnetic domains in the material. These domains undergo a stress-induced realignment during compression at 77 K. The reorientation of the magnetic domains are accompanied by at least a partial reorientation of the strains within the domains, so domain reorientation provides a source of strain to accommodate the applied stress. The local strains provided by domain reorientation occur at stresses much lower than required by work against the interatomic force constants. The interatomic force constants are expected to be approximately the same at 77 K as at 300 K.

It is interesting that the stress-strain curves at 77 K begin to curve upwards at stresses of approximately 25 MPa. We suggest that most of the domain reorientation mechanism has occurred at lower stresses, so at higher stresses the domain reorientation provides a decreasing amount of additional strain. Although the slopes of the curves increase with stress, we do not expect the slopes to become so large as at 300 K because plastic deformation occurs at stresses of approximately 40 MPa.

The stress-strain curves of Figs. 2 and 3 show hysteresis loops that indicate substantial energy dissipation. The fractional dissipation is calculated as the ratio of the area of the hysteresis loop to the mean area under the loading and unloading curves as shown in Table I. The energy lost is the product of the fractional dissipation with total potential energy stored within sample. The fraction of mechanical energy dissipated in the material is as large as 19.2% for the commercial purity sample. This is sufficient to make polycrystalline Tb–Dy an interesting material for the damping of mechanical vibrations at cryogenic temperatures.

Some minor loops were also measured for several cycles at restricted ranges of applied stress. These loops, also shown in Figs. 2 and 3, have larger slopes than the full loops, indicating smaller effects from domain reorientation. It also appears that the areas of these minor loops are small relative to the total dissipation. Evidently the magnetic domain orientations depend strongly on the mechanical history of the sample. The minor loops still show a large effect of magnetic domain reorientation on the effective Young's modulus, but it appears that these reorientations are more easily reversed than those that take place over a wider range of strain. This behavior is under further investigation.

We have completed measurements on the anisotropy of thermal expansion and stress-strain curves for three samples, for which these properties varied by 60%. We find an inverse relationship between the anisotropy in thermal expansion and the elastic moduli at 77 K. The relationship, if any, between the energy dissipation in the mechanical hysteresis loop and crystallographic texture of the sample is the subject of ongoing study. It appears that the magnetoelastic energy dissipation in the stress-strain hysteresis loops increases with the anisotropy of thermal expansion.

CONCLUSION

Measurements of stress-strain curves in the elastic range were performed on samples of polycrystalline $Tb_{76}Dy_{24}$ with differing degrees of crystallographic texture induced by cold rolling. We found the Young's moduli in compression tests to be reduced by as much as a factor of five at 77 K in comparison to their values at 300 K. This large reduction in Young's modulus at a temperature below the Curie point is attributed to magnetoelastic strains that accompany domain reorientations under the applied stress. The reduction in Young's modulus is larger for samples with a higher degree of crystallographic texture. A large mechanical hysteresis was also observed in the stress-strain curves at low temperatures. This hysteresis depends strongly on the mechanical history of the sample, and evidently on the microstructure of the material. The energy dissipation was as large as 19% per stress-strain cycle and may be of interest for the damping of mechanical vibrations at cryogenic temperatures.

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